Fermilab

Particle Physics Division
Mechanical Department Engineering Note

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Project:	DECAM
Title:	Primary Mirror Edge Supports: Forces
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Reviewer:	Under review.
Key Words:	CTIO, Blanco 4-meter telescope, primary mirror, edge supports

Abstract Summary:

Twenty-four (24) edge supports keep the primary mirror in the CTIO Blanco 4-meter telescope from sliding off the mirror cell. Refer to Appendix 1 for a brief description and images of the edge supports and cell. The edge supports are equally spaced around the mirror. The radial force exerted by a support on the mirror is generated by a counterweight and lever arm. The mirror pad base distributes the edge support force to four invar pads that are epoxied to the side of the mirror.

The force exerted on the mirror by the edge support depends on the mirror declination angle (angle from the zenith). The edge supports are vertical when the mirror is horizontal. They exert no radial force on the mirror in this position because the gravity vector acts axially through the center of the lever arm and through the center of the counterweight. The mirror cell supports the weight of the mirror in this position. At the other extreme, the edge supports are horizontal when the mirror is rotated to the vertical. (The calculations are done on the basis that the primary mirror can be rotated all the way to the vertical, i.e., declination angle of 90°. It can not actually be rotated that far.) They exert maximum force and carry the weight of the mirror in this position.

The force exerted on the mirror by an edge support also depends on its position on the mirror at any declination angle. When the mirror is at a declination angle of 90°, the supports at the apex and the very bottom generate the maximum force because the gravity vector acts at 90° to the lever arm, i.e., in the lever arm's plane of rotation. At all other positions the gravity vector acts at some angle other than 90° to the lever arm. Hence, the force exerted at each circumferential position depends on

the angle from the vertical to the radial line of action for the counterweighted lever arm.

CTIO personnel have calculated the radial forces needed to support the mirror at the horizon, i.e., at a declination angle of 90°. Their force diagram is in Figure 1. It is taken from Tim Abbott's presentation titled *Blanco primary mirror translations* given during the CTIO meeting held at Fermilab on May 18, 2005.

In this note, the forces needed to support the mirror at the horizon are calculated for two cases. The first case (Section 1.0) is for radial support only, like the CTIO calculation. The second case (Section 2.0) is for radial and tangential support of the mirror.

The extra weight that must be added to each end support as it exists today (according to the drawings) for it to provide the maximum restraining force in the radial support case (Section 1.0) is calculated in Section 3.0.

Applicable Codes: None.

Discussion and Results

Section 1

Radial reaction forces required to support the primary mirror are calculated via finite element analysis. It is assumed that no tangential forces develop at the edge supports. Mirror weight is taken as 34,000 pounds. The results are in Figure 2. The forces are slightly larger than the CTIO results in Figure 1: for position 1, 2,840 lbs vs 2,800 lbs; for position 2, 2,740 lbs vs 2,705 lbs; for position 3, 2,460 lbs vs 2,425 lbs; for position 4, 2,010 lbs vs 1,980 lbs; for position 5, 1,420 lbs vs 1,400 lbs; for position 6, 734 lbs vs 725 lbs. The maximum force at position 1 is used in the edge support counterweight calculations in Section 3.0.

Section 2

Radial and tangential reaction forces required to support the primary mirror are calculated via finite element analysis. It is assumed that tangential forces can develop at the edge supports. Mirror weight is taken as 34,000 pounds.

It looks like the end supports in positions 2 through 6 might provide some lateral restraint. Using these results in the edge support counterweight calculations is a topic for further consideration. Using the results from Section 1 to determine the counterweight is on the safe side because the forces are larger than the results in this Section. The effect of tangential forces on the epoxy joint between the edge support and the mirror will be covered in a future engineering note.

Radial reaction force results are in Figure 3. The radial reactions for this case are smaller than the case in Section 1 for radial only restraints: for position 1, 1,840 lbs vs 2,840 lbs; for position 2, 1,780 lbs vs 2,740 lbs; for position 3, 1,600 lbs vs 2,460 lbs; for position 4, 1,310 lbs vs 2,010 lbs; for position 5, 923 lbs vs 1,420 lbs; for position 6, 448 lbs vs 734 lbs.

Tangential reaction force results are in Figure 4. The tangential reaction forces are: for position 1, 0 lbs; for position 2, 282 lbs; for position 3, 550 lbs; for position 4, 792 lbs; for position 5, 1,010 lbs; for position 6, 1,250 lbs.

Section 3

In part 1.0, the total moment generated by the counterweight assembly about the lever arm's pivot point is calculated. This is done by summing the moment contribution of all components. The moment for a component is found by multiplying the weight of the component by the dimension between its center-of-gravity and the pivot point. Component weight and distance from the pivot point are calculated using dimensions on the drawings. It is assumed that only 5 trim weights are installed on each edge support. This is the nominal quantity of trim weights specified in the edge support bill of material. The additional weight that must be added to the support for it to exert the maximum radial reaction force in Section 1.0 is calculated.

The weight of all components on the counterweight side is calculated at 150.5 pounds. The effective distance between the pivot point and the 150.5 pound equivalent concentrated force is calculated at 23.67". These two results include the additional weight, 15.75 pounds, added to balance the maximum radial reaction force in Section 1.0.

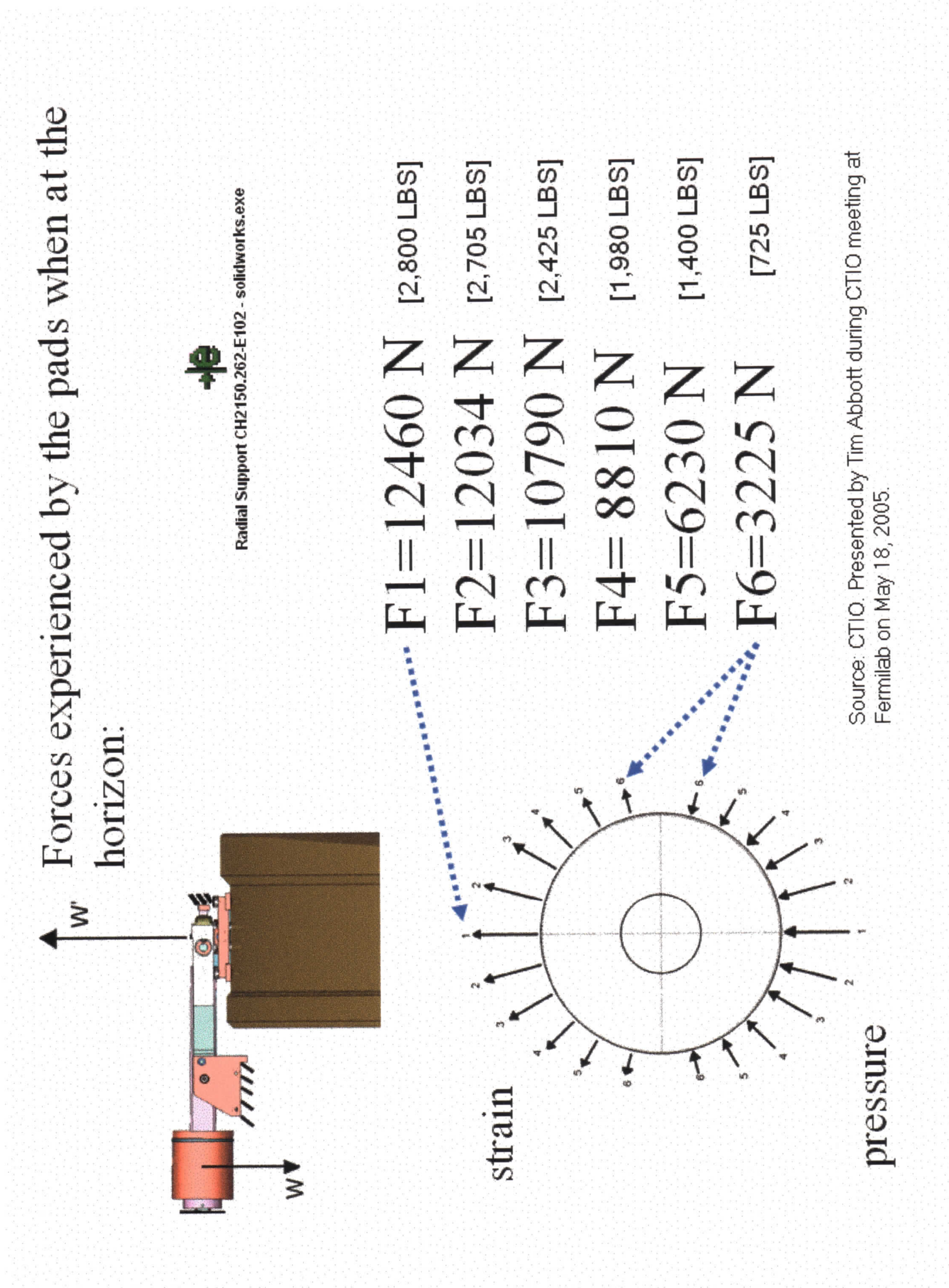
In part 2.0, the 150.5 pound counterweight force and effective offset of 23.67" is used to calculate the force exerted by an edge support on the mirror as a function of declination angle for an edge support positioned at the top of the mirror, i.e., position 1 in Figure 1. Part 2 results include the additional 15.75 pounds added to balance the maximum radial reaction force in Section 1.0.

In part 3.0, the 150.5 pound counterweight force and effective offset of 23.67" is used to calculate the force exerted by an edge support on the mirror as a function of both declination angle and circumferential position on the mirror, i.e., positions 2 through 6 in Figure 1. The results are shown on page 7 of the hand calculations. Part

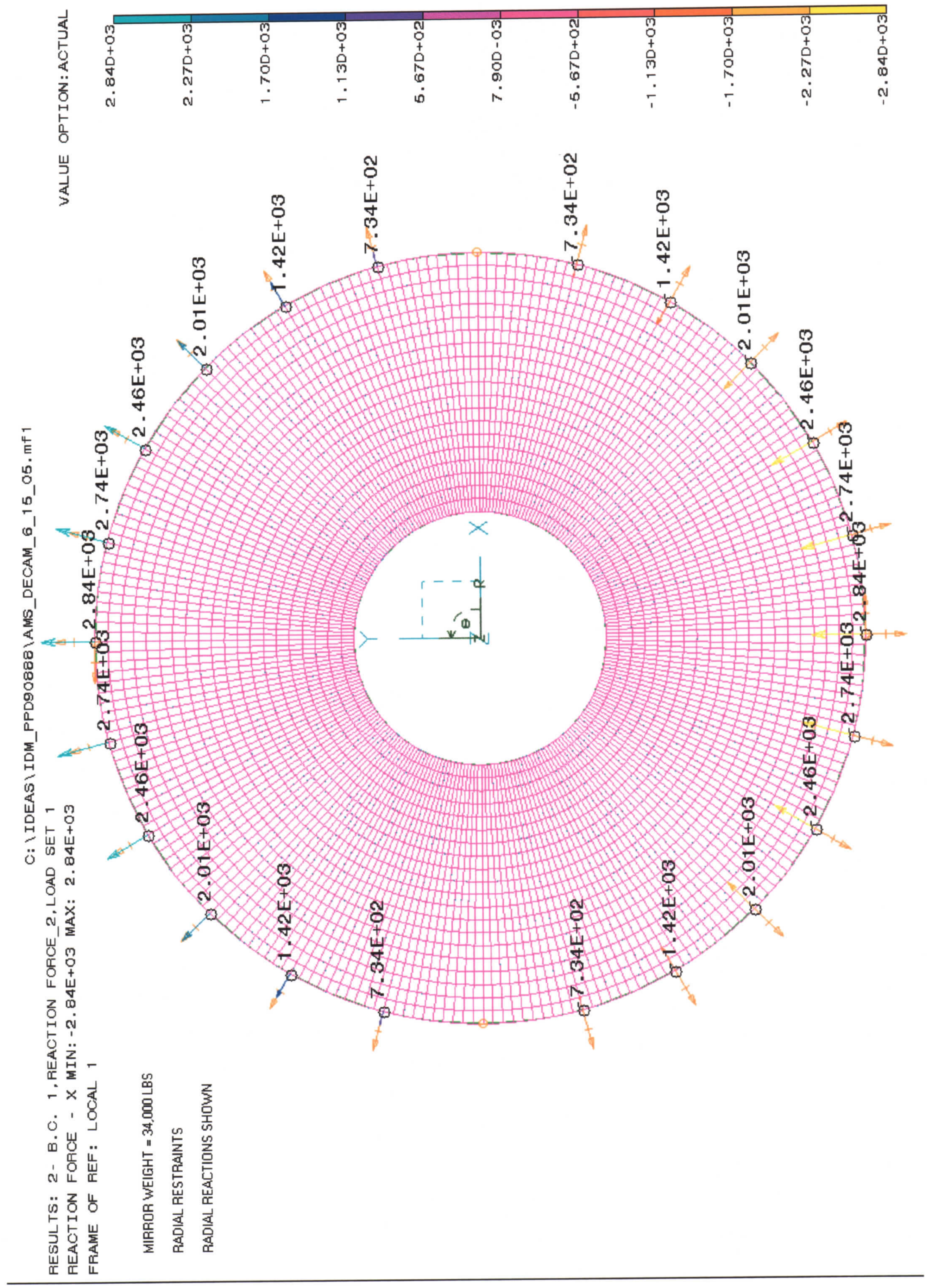
3 results include the additional 15.75 pounds added to balance the maximum radial reaction force in Section 1.0.

For comparison, the force exerted by an edge support on the mirror as a function of both declination angle and circumferential position on the mirror is also calculated without the additional 15.75 pounds needed for the support to exert the maximum radial reaction force in Section 1.0. Essentially, this calculation is nominally for the supports as they exist today (according to the drawings). The results are shown on page 8 of the hand calculations. For this calculation, the weight of all components on the counterweight side is calculated at 134.76 pounds. The effective distance between the pivot point and the 134.76 pound equivalent concentrated force is calculated at 22.625". These numbers can be found on the bottom of page 3 of the hand calculations. As seen in the results on page 8, the edge supports as they exist today exert more radial force than required when tangential restraint is included in the calculation.

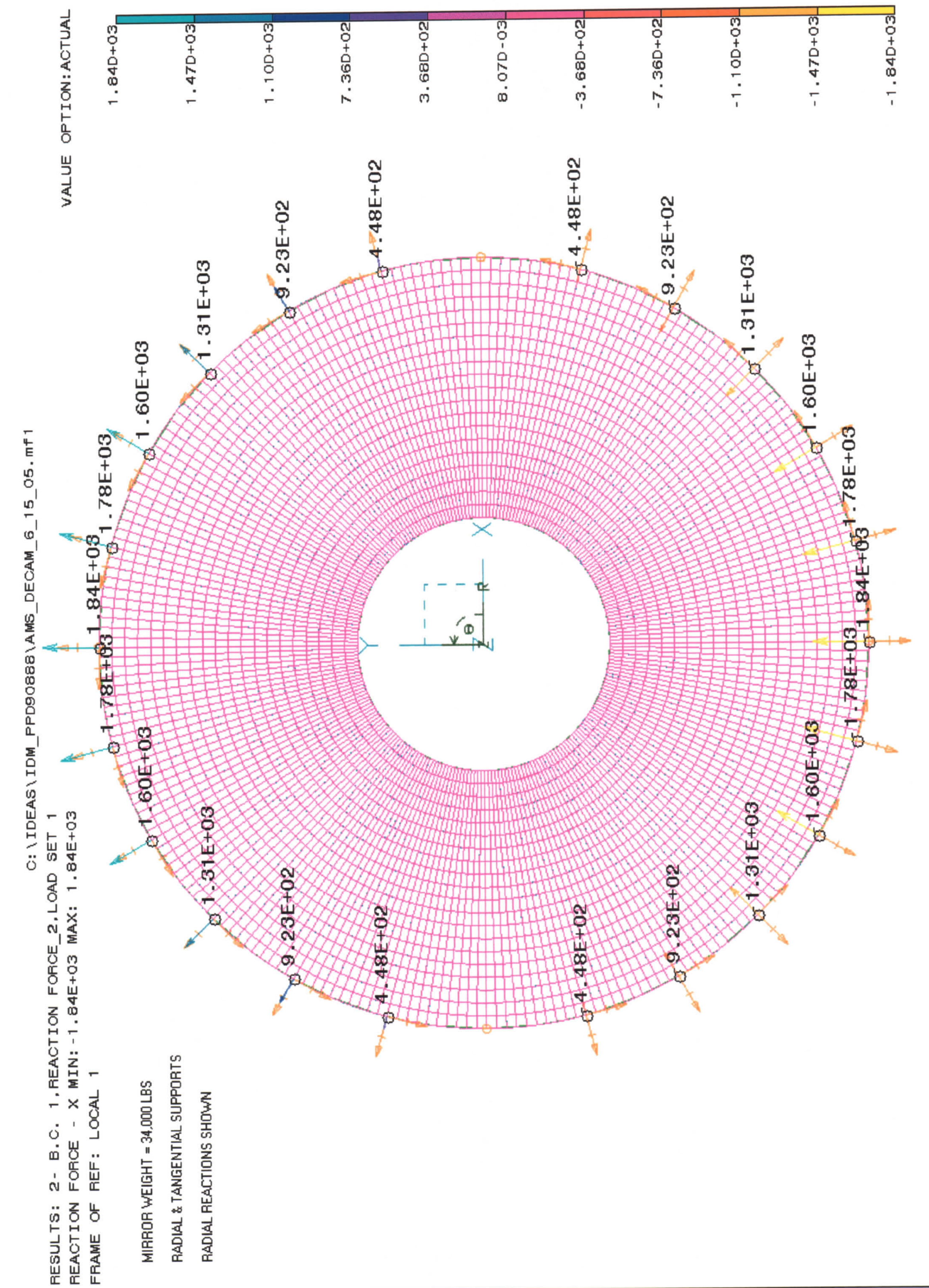
Figure 1


Forces experienced by the pads when at the horizon:
W'
W
Radial Support CH2150.262-E102 - solidworks.exe
strain
pressure
F1=12460 N [2,800 LBS]
F2=12034 N [2,705 LBS]
F3=10790 N [2,425 LBS]
F4=8810 N [1,980 LBS]
F5=6230 N [1,400 LBS]
F6=3225 N [725 LBS]
Source: CTIO. Presented by Tim Abbott during CTIO meeting at Fermilab on May 18, 2005.

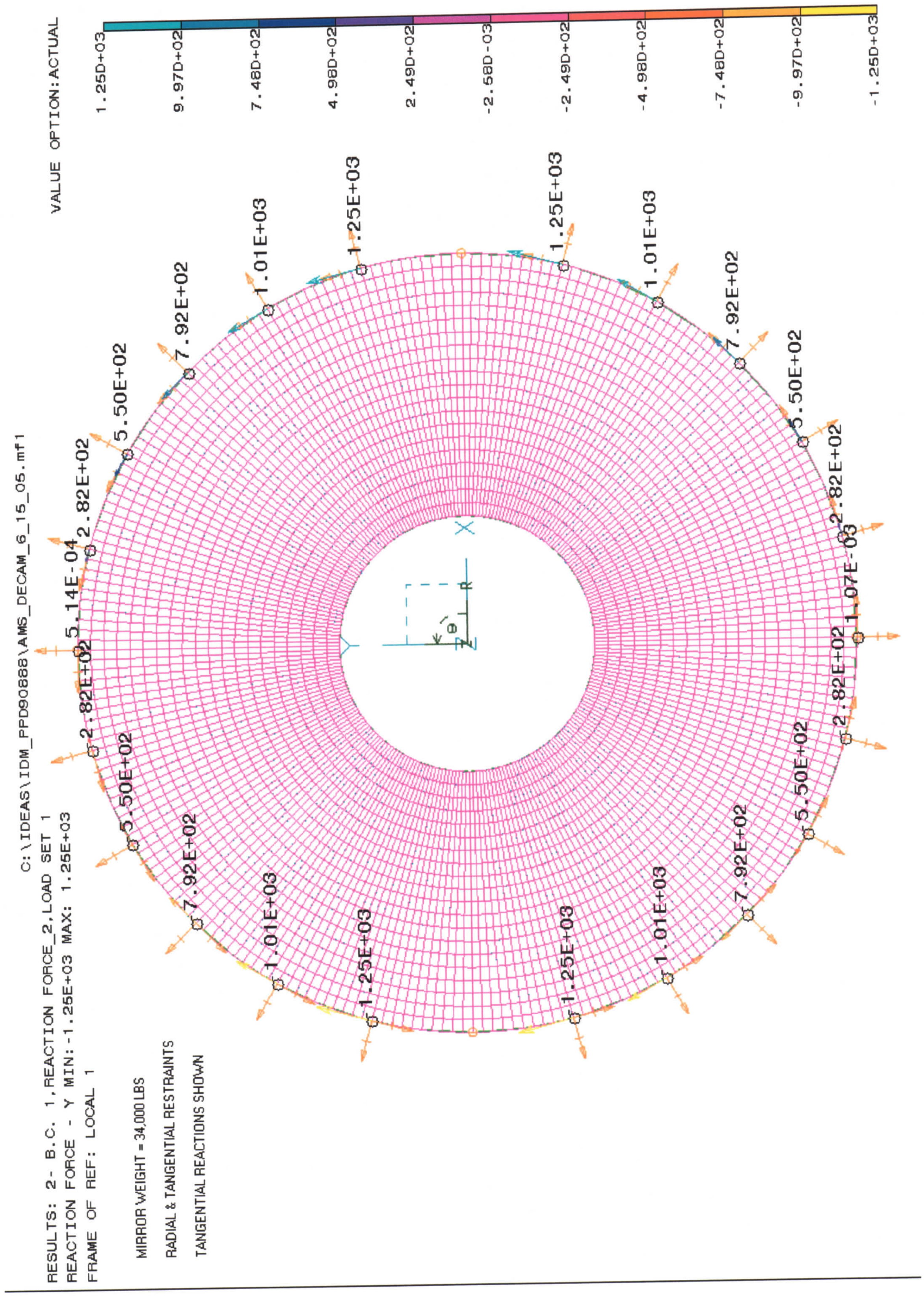
Section 1 - Figure 2



Section 2 - Figure 3



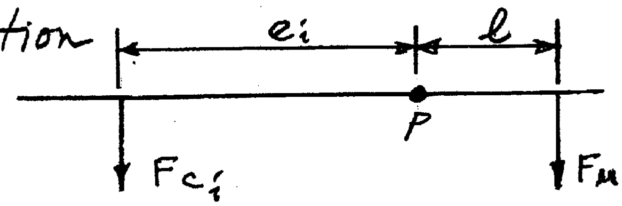
Section2 - Figure 4



FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	3.0			1

SUBJECT	NAME	DATE	REVISION DATE
CTIO primary mirror edge supports Maximum applied radial force	A.M.Stefanik	6/23/05	

1. Calculate F_m in horizontal position (at top of the mirror)



$\Sigma M_p = 0$

$F_m \ell - \Sigma Fc_i e_i = 0$

$$F_m = \frac{\Sigma Fc_i e_i}{\ell} \qquad \ell = 1.25''$$

Counterweights	F_i (Lbs)	e_i (in)	$Fc_i e_i$ (in-Lbs)
• 3x2x0.065 steel tubing	5	16.625	83.1
Bucket for the lead: -Shell	3	25.75	77.2
- Bottom plate	0.5	29.7	14.9
• Ring: 4½"x3½"x 1.12" steel	2	30.31	60.6
• 4 holes in the ring: 5/16" ϕ	0.04	30.55	-1.2

• 3x2x0.065 steel tubing

$F = 2.153 \frac{Lbs}{\cancel{ft}} * \frac{28}{12} \cancel{ft} = 5$ Lbs

$e = \frac{(28-0.75)}{2} + 3 = 16.625''$

Bucket for the lead:

-Shell

$F = [\pi(7.0589)(0.0589)8]\, \cancel{in^3} * 0.283\, Lb/\cancel{in^3}$
$= 3$ Lbs

$e = 28-(0.75+0.5+4)+3 = 25.75''$

- Bottom plate

$F = \left[\frac{\pi}{4}(6.95)^2 - (3.2)\right] \cancel{in^2} * 0.0589 \cancel{in} * 0.283 \frac{Lb}{\cancel{in^3}}$

$= 0.5$ Lbs

$e = 28-(0.75+0.5) - \frac{0.0589}{2} + 3 = 29.7$

• Ring: 4½"x3½"x 1.12" steel

$F = 21.36 \frac{Lbs}{\cancel{ft}} * \frac{1.12}{12} \cancel{ft} = 2$ Lbs

$e = 28-0.75+3-0.5+1.12/2 = 30.31$

Note: Ring thickness = [4½-3½]/2 = ½"

• 4 holes in the ring: 5/16" ϕ

$F = [\pi(5/16)^2/4](½)\cancel{in^3}(0.283\, Lb/\cancel{in^3})(4) = 0.04$ Lbs

$e = 28-0.75+3-0.5+0.8 = 30.55''$

Counterweights	F_i (Lbs)	e_i (in)	$F_{ci} e_i$ (in - Lbs)
• Lead	93.54	25.75	2,408.7

$F = 104 - (5 + 3 + 0.5 + 2 - 0.04)$
$= 93.54$ Lbs
$e = 25.75''$

Up to this point - $\Sigma =$ 2,643.3

$Fm = \dfrac{2643 \text{ in Lbs}}{1.25 \text{ in}} = 2{,}114$ Lbs

	F_i (Lbs)	e_i (in)	$F_{ci} e_i$ (in - Lbs)
• Lever : Steel shaft	0.7	4.19	2.9

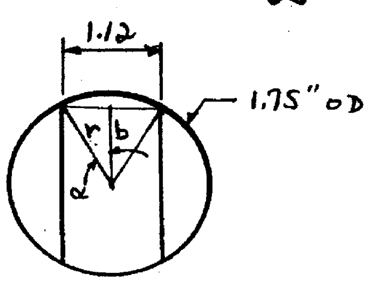
$F = \frac{\pi}{4}\left[(1.1873^2)(2.38) - (0.375)^2(1.1873)\right] \cancel{in^3} \cdot 0.283 \frac{Lb}{\cancel{in^3}} = 0.7$ Lbs

$e = (2.38/2) + 3 = 4.19''$

	F_i (Lbs)	e_i (in)	$F_{ci} e_i$ (in - Lbs)
	17.7	17.19	304

$F = \left[\frac{\pi}{4} (1.75)^2 (29.38 - 2.38 - 1)\right] \cancel{in^3} * 0.283 \frac{Lb}{\cancel{in^3}} = 17.7$

$e = \frac{(29.38 - 2.38 - 1)}{2} + \frac{2.38}{2} + 3 = 17.19''$



	F_i (Lbs)	e_i (in)	$F_{ci} e_i$ (in - Lbs)
	0.5	30.69	15

$\sin\alpha = \left(\frac{1.12}{2}\right) / (1.75/2) \Rightarrow \alpha = 39.8^\circ$

$\left(\frac{1.12}{2}\right)^2 + b^2 = (1.75/2)^2 \Rightarrow b = 0.67$ in

$F = \left[\pi \frac{(1.75)^2}{4} * \frac{4(39.8^\circ)}{360^\circ} + \left(\frac{1.12}{2}\right)(2 \times 0.67)\right] in^2 * 1 \, in * 0.283 \frac{Lb}{in^3} = 0.5$ Lbs

$e = 29.38 - 2.38/2 - 0.5 + 3 = 30.69$

Counterweights	F_i (Lbs)	e_i (in)	$F_{ci}\,e_i$ (in-Lbs)
Set screws Qty=4	0.16	30.55"	4.9

Diameter = 5/16"
Average length = (3/4 + 2)/2 = 1 7/8"
$F = 4\left[\left(\pi (5/16)^2/4\right) \times (1.875)\right] in^3 \times 0.283\ Lb/in^3 = 0.16\ Lbs$
$e = 28 - 0.75 + 3 - 0.5 + 0.8 = 30.55''$

Pivot yoke	9.45	0.9	8.5

F = 9.45 Lbs } Calculated via
e = 0.9" } IDEAS 3D Model

Up to this point − $\Sigma = 2{,}978.6$

$F_m = 2{,}979/1.25 = 2{,}383$ Lbs

Trim weight	2.25	31.3	70.4

(5 nominal required)
Assume the material is steel.
Assume the dimensions are: 5.35" OD x 0.625" ID x 0.071 in thickness
Note: Trim weight material and dimensions are assumed until we obtain a copy of the drawing.

$F_{one\ plate} = \left[\frac{\pi}{4}(5.35^2 - \cancel{0.625^2})\,0.071\right] \cancel{in^3} \times 0.283 \frac{Lb}{in^3} = 0.45\ Lbs$

Neglect the ID to account for the fastener used to hold the trim weights to the support.

For 5 plates: $F = 5(0.45) = 2.25$ Lbs
$e = 29.38 - 2.38/2 + 0.071(5/2) + 3 = 31.3''$

Conclusion up to this point for F_m, F_c & e_c: $\Sigma = 3{,}049$ in-Lbs

$F_m = 3{,}049/1.25 = 2{,}439$ Lbs
Total counterweight force = 134.76 Lbs = F_c
Calculate "e" for 134.76 Lbs
"e" for counterweight force = 3,049/134.76 = 22.625"
Following the calcs on pg 6, up to this point $F_m(\theta, \alpha) = 2{,}439.156 \sin\theta \cos\alpha$. Numerical values are tabulated on page 8.

Counterweights	F_i (Lbs)	e_i (in)	$F_{ci}e_i$ (in-Lbs)

- Calculate how much weight must be added to the support for it to produce the maximum radial reaction force calculated in the FEA model for the case of having only radial restraints and the mirror vertical.

Maximum radial reaction force (FEA) = 2,840 Lbs

$\Delta_F = 2,840 - 2,439 = 401$ Lbs

← Page 3, calculated value for F_m

$\Sigma F_{ci}e_i = 2,840$ Lbs (1.25 in) = 3,550 in-Lbs

$\Delta_m = 3,550 - 3,049 = 501$ in-Lbs

← Page 3, calculated value for $\Sigma F_{ci}e_i$

Add 35 more trim weights.

$F = 35(0.45) = 15.75$ Lbs

$e = 29.38 - 2.38/2 + 0.071(5/2) + 3 + 0.071(35/2) = 32.6''$

$15.75 \times 32.6 = 513.45$ in-Lbs

Grand total at this point $\Sigma = 3,562$ in-Lbs

$F_m = 3,562/1.25 = 2,850$ Lbs > 2,840 Lbs ok

- Conclusion for F_m, F_c and e_c:

$F_m = 2,850$ Lbs > 2,840 Lbs ok

Total counterweight force = 150.5 Lbs = F_c

Calculate "e" for 150.5 Lbs –

"e" for counterweight force = 3,562/150.5 = 23.67''

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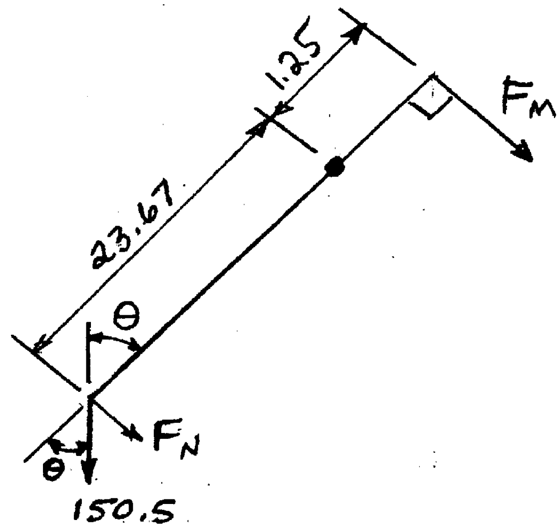
SUBJECT	NAME AMS	
2.0	DATE 6/23/05	REVISION DATE

Calculate Fm as a function of declination angle at top position on the mirror

$$F_m(\theta) = \frac{F_N\,(23.67)}{1.25}$$



$\theta \equiv$ declination angle

$\theta = 0°$ with support in vertical position, i.e., Fm collinear with the 150.5 Lb counterweight

$\sin\theta = F_N / 150.5$

$F_N = 150.5 \sin\theta$

$\therefore F_M(\theta) = 150.5 \sin\theta (23.67)/1.25$

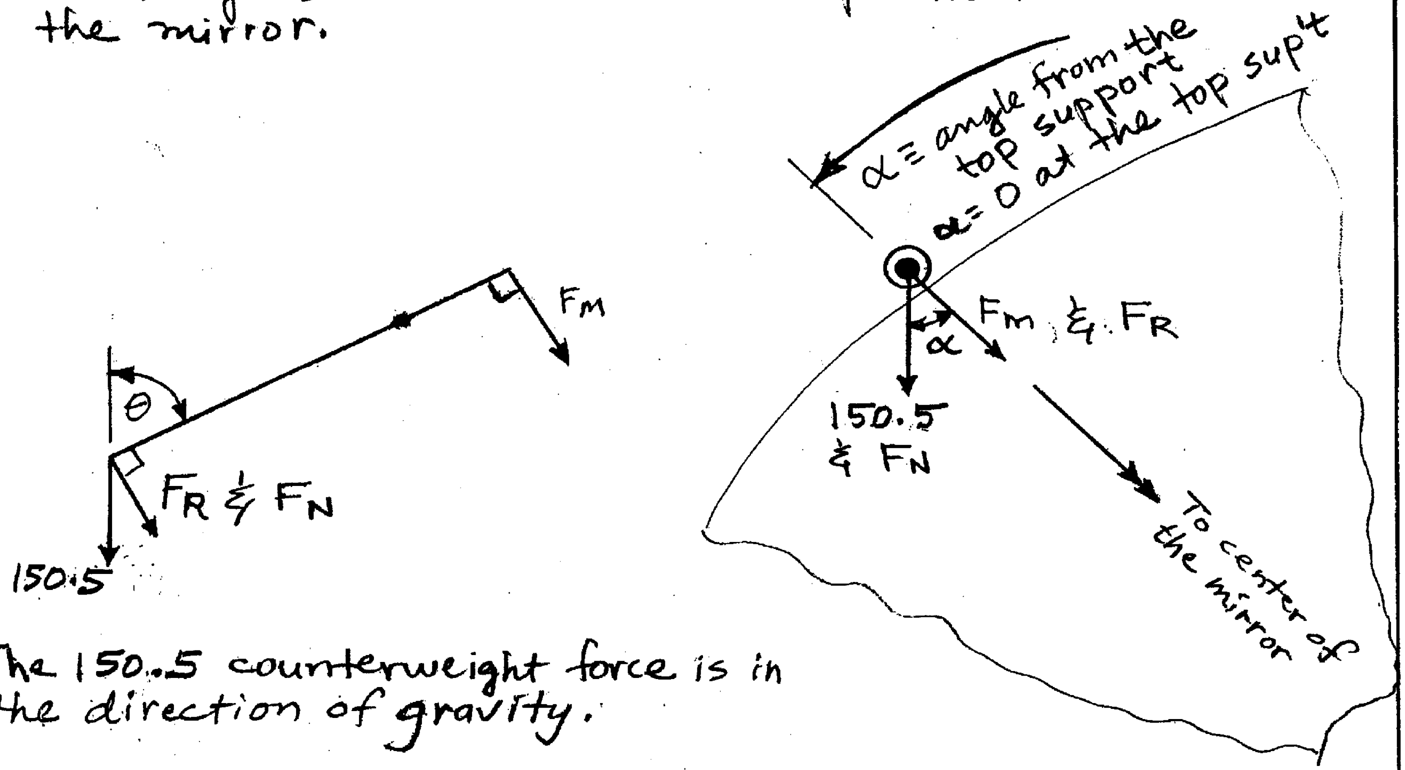
$= 2{,}849.868 \sin\theta$

θ	Fm
0°	0 Lbs
10°	494.9
20°	974.7
30°	1,424.9
40°	1,831.9
45°	2,015.2
50°	2,183.1
60°	2,468.1
70°	2,678
80°	2,806.5
90°	2,849.9

Calculate Fm as a function of declination angle and position around the mirror

Refer to the sketch in § 2.0.

Fm is always ⊥ to the mirror and points to the center of the mirror.



The 150.5 counterweight force is in the direction of gravity.

Both FR & FN are in a plane ⊥ to the edge support.

$\cos\alpha = F_R / F_N \Rightarrow F_R = F_N \cos\alpha$. Substitute FN from § 2.0.

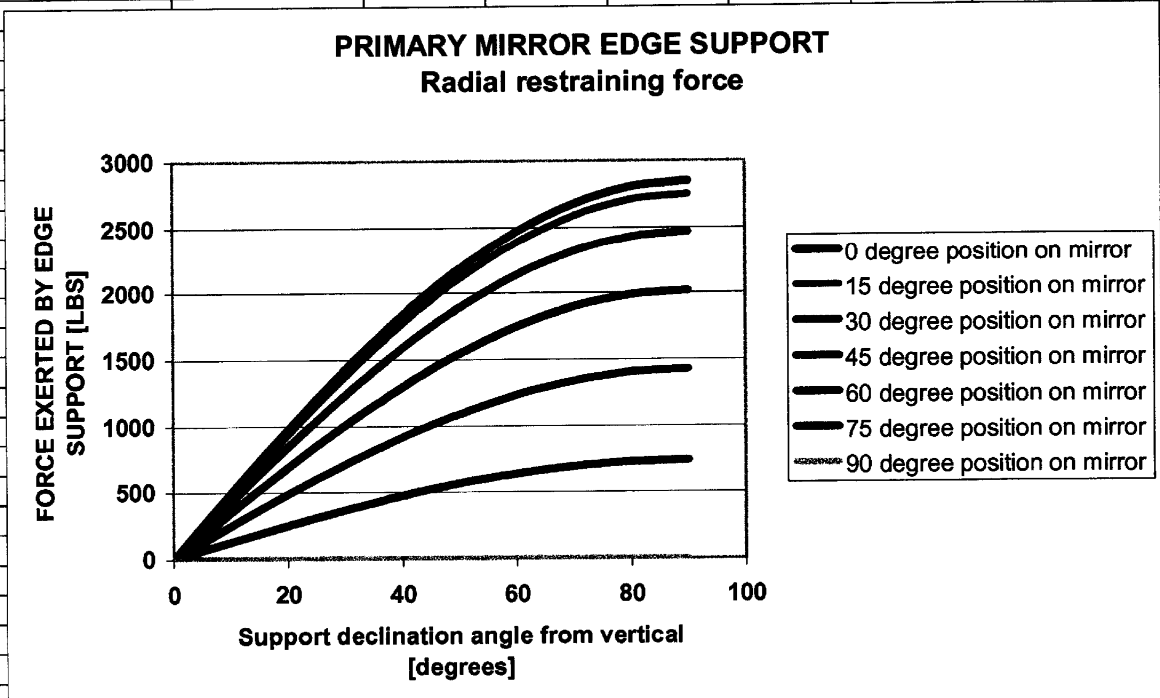
$\therefore F_R = 150.5 \sin\theta \cos\alpha$. Follow the first formula in § 2.0:

$\therefore F_m(\theta,\alpha) = 150.5 \sin\theta \cos\alpha \,(23.67/1.25)$

$= 2{,}849.868 \sin\theta \cos\alpha$

Numerical values are tabulated on page 7.

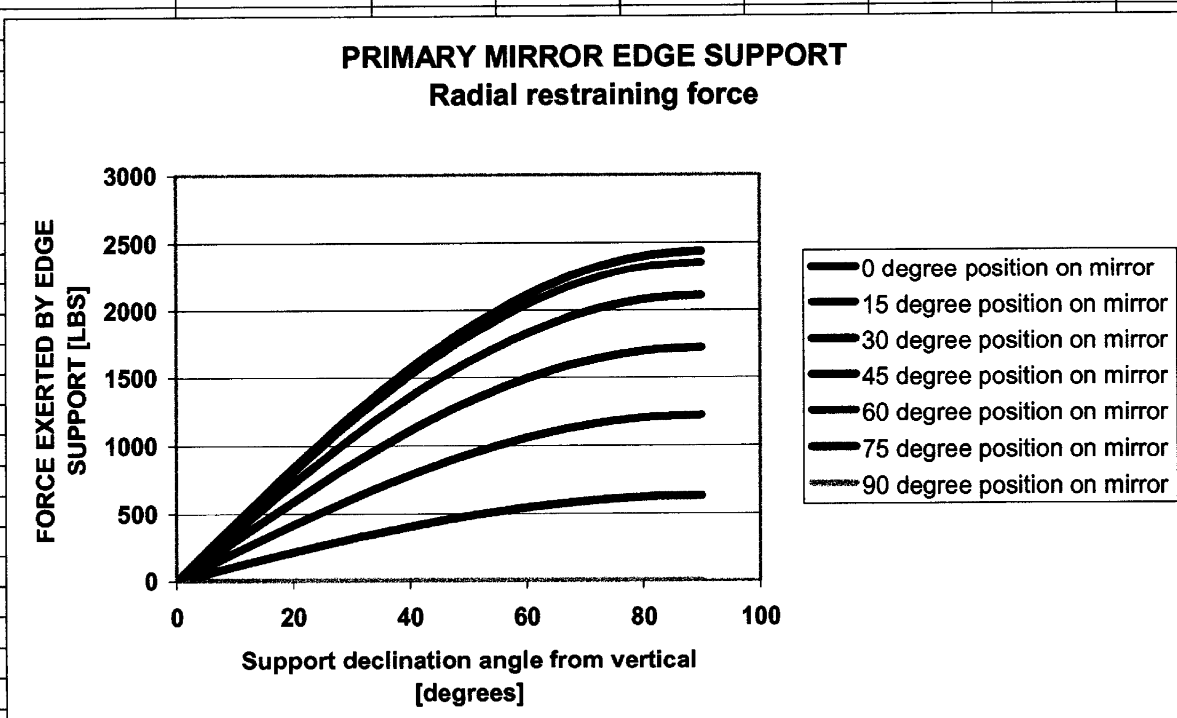
Calculate radial restraining force exerted on the mirror by the edge supports as a function of declination angle and position around the mirror:								
2849.868			Position on the mirror from the top [degrees] Top position = 0 when mirror is declined 90 degrees.					
For the case of having only radial restraints (no tangential restraints)	Declination angle from the vertical [degrees]	0	15	30	45	60	75	90
Support vertical, Mirror horizontal	0	0	0	0	0	0	0	0
	10	495	478	429	350	247	128	0
	20	975	941	844	689	487	252	0
	30	1425	1376	1234	1008	712	369	0
	40	1832	1769	1586	1295	916	474	0
	45	2015	1946	1745	1425	1008	522	0
	50	2183	2109	1891	1544	1092	565	0
	60	2468	2384	2137	1745	1234	639	0
	70	2678	2587	2319	1894	1339	693	0
	80	2807	2711	2431	1985	1403	726	0
Support horizontal, Mirror vertical	90	2850	2753	2468	2015	1425	738	0



Calculate radial restraining force exerted on the mirror by the edge supports as a function of declination angle and position around the mirror:

2439.156

For the case of having both radial and tangential restraints	Declination angle from the vertical [degrees]	Position on the mirror from the top [degrees] Top position = 0 when mirror is declined 90 degrees. 0	15	30	45	60	75	90
Support vertical, Mirror horizontal	0	0	0	0	0	0	0	0
	10	424	409	367	299	212	110	0
	20	834	806	722	590	417	216	0
	30	1220	1178	1056	862	610	316	0
	40	1568	1514	1358	1109	784	406	0
	45	1725	1666	1494	1220	862	446	0
	50	1869	1805	1618	1321	934	484	0
	60	2112	2040	1829	1494	1056	547	0
	70	2292	2214	1985	1621	1146	593	0
	80	2402	2320	2080	1699	1201	622	0
Support horizontal, Mirror vertical	90	2439	2356	2112	1725	1220	631	0



Appendix 1

Blanco 4-Meter Shutdown October 2002

Tim Abbott

At the time of writing, the Blanco 4-meter telescope shutdown is nearing completion. The first priority for this shutdown was to repair broken radial supports. Two dozen of these edge-mounted, mechanical assemblies reduce sagging of the primary mirror under gravity by distributing the load; they push from below and pull from above when the mirror is tilted, with the force vectors passing through its center of gravity.

The supports are attached to the Cervit primary via epoxied Invar pads. In some cases, the epoxy has failed. The supports are nearly impossible to access without dismantling the telescope and it is difficult to detect precisely when they detach from the mirror, and therefore under what circumstances. On average, only one or two of these supports break during a period of roughly two years, but this time a total of four supports had given way in the two years since the last re-aluminization of the primary. The risk of further breakage and possible disabling of the telescope forced our hand, even though we had hoped to wait another two years before re-aluminizing, and thus gaining access to the supports. As it is, we are now cleaning the mirror with both water and CO_2 snow.

Given that the repairs require dismantling the telescope, and thus closing it for a minimum of ten days, we decided to extend the downtime to two weeks and take the opportunity to re-aluminize the primary as well. A number of other tasks were also scheduled and completed:

- New mirror cover actuators have been installed—the new mirror cover stretches the capability of the old actuators, requiring that the telescope be brought to north station to open and close; the new actuators are considerably more powerful.
- A new Cassegrain guide camera has been installed—permitting region-of-interest and therefore faster guiding.
- Telescope grounding paths were improved, perished compressed-air lines were replaced, and cables were rerouted to bypass an ancient and failing cable run.

continued

Blanco Shutdown continued

- Microswitches and self-illuminating cameras have been installed on each support pad to provide instant notification of broken pads and the ability to inspect their condition remotely.

Considerable thought was put into identifying plausible causes for the support breaks, and as many of these as possible were addressed. Old epoxy was stripped and the surfaces carefully prepared to create a good bond. Previously, joints were repaired after re-aluminization of the primary. Then the epoxy cure was accelerated by heating with lamps, and the supports were neither disassembled prior to reinstallation nor lubricated—both of which might have relieved differential thermal expansion stresses. Cervit and Invar have very low thermal expansion, but Invar's is greater than Cervit's and considerable forces can still develop. This time, repairs were done before re-aluminization, the joints were cured at ambient temperatures for a full week, the supports were removed after the repair, and lubrication was applied to critical bolted surfaces.

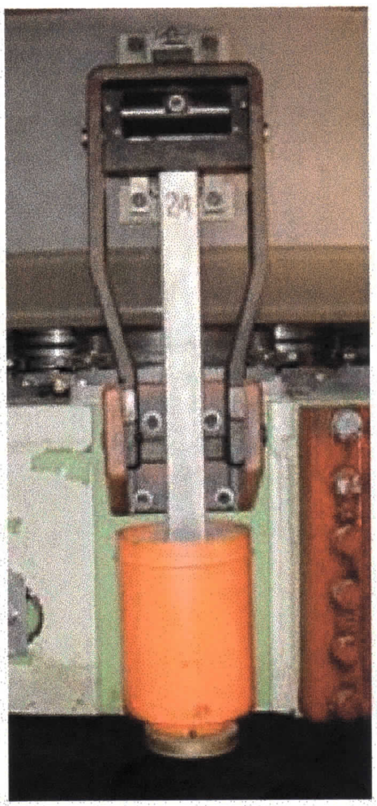


Figure 1. One of the infamous edge supports, mounted on the mirror cell at bottom and still attached to the mirror at top.

No evidence was found of binding in the supports from corrosion (as a result of either condensation or possible leaks in the wet-wash seal). All repairs survived strain tests 50 percent greater than the nominal specification before the telescope was reinstalled.

Suspecting that mechanical misalignment might be a contributory cause, we carefully measured the relative positions of the mirror, its cell, and the supports. A full analysis is pending, but we discovered that the mirror was mounted in the cell at 2.3 millimeters below its nominal position. There is no obvious reason for this but it may be the accumulated result of repeated recollimations and other adjustments experienced by the telescope. Since such a displacement would generate a torque in the tilted mirror via the edge supports and produce lateral forces in the epoxy joints, we corrected the error. A gratifying sanity check was provided on reassembling the telescope: the run of below-mirror hard point loading with telescope altitude is now a clean sinusoid whereas previously it had been lopsided, exactly as would be expected.

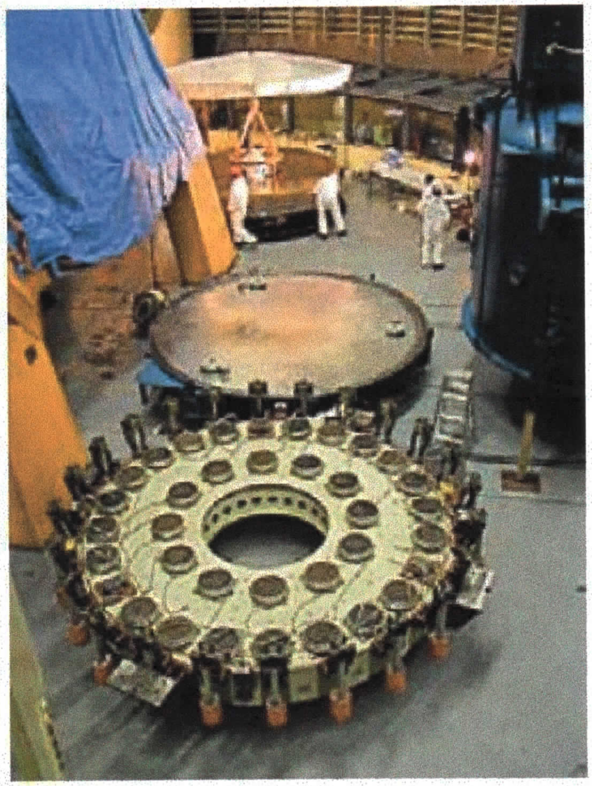


Figure 2. The dismantled Blanco telescope. In the foreground is the mirror cell, the edge supports around the edge and two circles of active optics supports within. At the rear, the primary mirror, freshly stripped of its aluminum coating, is prepared for lifting onto the bottom of the re-aluminization chamber in the middle of the picture.

Despite these efforts and to our considerable distress, one of the repaired edge supports failed almost immediately after we started moving the telescope. The proximate cause of the break may have been the result of a procedural error, but it seems clear that the supports should be able

continued

Blanco Shutdown continued

to take considerably more strain than they are suffering if everything is per design. Nevertheless, we have considerably improved our knowledge of the telescope through this shutdown, and the new capability to monitor the condition of the supports will hopefully provide us with unambiguous information in the event of additional breaks and perhaps lead us to a permanent cure.

The final tasks of the shutdown involve confirming that the telescope is operating correctly and tweaking the optical alignment as necessary. Thus far, all seems well.

It is impossible to mention everyone who has made a crucial contribution to this work, but Oscar Saá, Roberto Tighe, Gale Brehmer, Andrés Montané, Eduardo Huanchicay, Ricardo Schmidt, and their teams have all played central roles at one point or another. In particular, the frequently unsung mechanics have been a pleasure to watch; their deft handling of tens of tons and metal and glass made graceful choreography of dangerous work.

Figure 3. The US Ambassador to Chile paid us a visit during the shutdown. Back row: Gale Brehmer, Manuel Martinez, Javier Rojas, Tim Abbott, and Oscar Saá. Middle row: Eduardo Huanchicay, Andrés Montané, Ambassador William R. Brownfield, Malcolm Smith, and Wilson Muñoz. Front row: Eduardo Aguirre and Jorge Briones.